A Simple Hybrid Testing Approach For Dynamic Analysis of Civil Structural Control Devices

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ABSTRACT

Effective real-time testing of structural control devices relies on a hybrid test system that couples virtual structures under dynamic loading with physical sub-structures or devices in a dynamic test rig. The use of sensors and actuators in a closed-loop feedback system maintains the dynamic equilibrium of the overall system comprising the physical test article and virtual modelled structure. The virtual-real hybrid testing method thus alleviates much of the time and cost associated with full-scale testing and enables tests that would be infeasible without full-scale complete structural tests. Thus, it can reduce the uncertainty in designing such a full scale test by testing, in hybrid hardware in the loop fashion, the devices and sub-systems required to ensure the best overall full-scale experimental design. Hence, a major outcome is the savings in the cost, time and complexity of the resulting full scale experiment. To accomplish this goal, this research presents simple, cost-effective and robust hybrid test system, and outlines solutions to the major issues faced in developing any hybrid system. The overall approach is centred on the dSpace™ real-time control system development tool. The major issues in developing a hybrid system are: minimal signal processing lag, optimised sensing resolution and bandwidth, and efficient model computation. All three affect the ability of the system to maintain dynamic equilibrium of the overall virtual-physical system, and thus provide an accurate test. The final system readily accommodates non-linear-single and multi-degree-of-freedom models and an operating bandwidth of 1 kHz. Test results and experimental outcomes are based on studies of a linear single degree of freedom structure and a non-linear rocking wall system that includes impact loads and timing subject to random ground motions. The results clearly illustrate system simplicity, efficacy and how they can be used to illustrate the potential outcomes of full scale experiments but at simple, fast low cost level.

Keywords: hybrid testing, pseudo-dynamic testing, real-time control, virtual structure, simulation, structural control devices,

1. INTRODUCTION

Recent decades have witnessed widespread applications of mechatronics for systems monitoring and control, ranging from machine components such as bearings, precision machines, automotive systems, aerial vehicles to civil structures. In particular, [1-3] discuss a variety of techniques like acoustic emission sensing, embedded systems, and clustering algorithms for real-time monitoring of machine structures and rotating tools. In civil structures, with the rapid advancement of experimental test methods, numerical simulation, and high-speed communication networks, it is possible to distribute geographically the testing of structural systems using hybrid experimental-computational simulation. Many researchers have developed various hybrid test methods for substructures [4-9].

Notably, modelling and simulation plays an important role in the development of a hybrid testing method for civil structures, substructures and structural control devices. For a simulation model to reproduce the actual behaviour in the virtual environment, a high-fidelity model of the complete system must be available. Even with an accurate simulation model, researchers are confronted with difficulties in testing substructures and devices in the real environment. In the case of civil engineering, testing with the full-scale complete structure is not feasible. To overcome the impracticality with full-scale testing, and shorten the testing cycle; we has developed a hybrid test system. The hybrid test system comprises three essential components: 1) virtual structures under dynamic loading; 2) physical sub-structures or devices in a dynamic test rig; and 3) a real-time system capable of melding this model with the test system actuators and sensors in a seamless fashion.

The purpose of the hybrid test system is to test elements or sub-structures as if they were physically in place in a real structure without having to create the full scale system. A test procedure for new sub-structures or elements that allows them to be rapidly tested in a variety of structural applications is a great tool for the structural engineering researcher, in particular for testing new methods of design, construction or finishing, as well as novel devices or systems. More rapid testing turnaround for full scale testing without the need for all the resources required ensures greater testing and thus greater certainty in the final application. In this particular mechatronics system development, since the control of the physical device being tested is determined by the response of the main structure, it is essential that the test be carried out in real time to emulate the performance of the device in the real environment.

To achieve this goal what is required is twofold: 1) a detailed (non-linear) model that captures the essential dynamics of the main structure at the proper level of detail so that a real-time numerical integration can be performed; and 2) a real-time system capable of melding this model with the test system actuators and sensors in a seamless fashion. To this end, this Hybrid testing procedure has been developed that allows rapid implementation of an experiment set up. This approach utilises the dSpace™ real-time feedback control system to create this system both rapidly and without error.

In the case presented here its is necessary to use a real time testing procedure, as the control of the physical device being tested is determined by the response of the main structure. Hence, it is essential that the test be carried out in real time as when in place the device will have to perform in real time. Pan et al [12] and Takahashi & Fenves [13] offer a similar type of testing with the additional feature of being connected over the web where different aspects of the setup can be located in a wide special area. This feature, however, adds complexity and the project focuses on the geographic distribution of the test sub-structures, whereas the process described here was developed with the focus on the implementation of a number of applications that would benefit structural research.

This paper presents a novel process based on commercially readily available real-time system products that use Matlab® and Simulink®. In developing the cost-effective hybrid test system, the overall approach is centred on the dSpace™ real-time control system development tool. The major issues in developing a hybrid system are: minimal signal processing lag, optimised sensing resolution and bandwidth, and efficient model computation. All three factors affect the ability of the system to maintain dynamic equilibrium of the overall virtual-physical system, and thus provide an accurate test. The final system readily accommodates non-linear-multi-degree-of-freedom models and a 1 kHz operating bandwidth.

2. HYBRID TESTING METHODOLOGY

Testing of mechatronics systems, machineries or civil structures in virtual environment relies on the model of the systems. The fidelity of the results depends on the accuracy of the model entirely. On many occasions, some parts and modules (sub-systems) of the system cannot be modelled accurately. The idea of hybrid testing is a hybrid approach where testing is carried out by operating real components or modules in connection with real-time simulated components.

Figure 1 shows the civil structure under study, and Figure 2 the computer model. The highlighted area is the structure to be tested. In this research work, real-time control system hardware and software based on dSpace™ was employed. The controlled process (consisting of actuators, physical processes, and sensors) comprises simulated components or real components.

The process is similar to that for pseudo-dynamic testing with the structure model (the well understood part of the system) computationally modelled, while the sub-system or device is physically built. The two systems are linked by a dynamic test rig or actuators that provide the commands dictated by the main structure response, while measuring devices return the response of the sub-system to the main structure. This virtual-real interface is managed by a real-time control system development tool (the dSpace™ system), which is also utilised as the data gathering and storage system.

Sensors on the test structure or system measure both forces and motions that are fed back to the model to determine the equilibrium response as part of a whole structure. The motions are measured to ensure that what was commanded was received by the system and to ensure precision in an inner feedback loop if required. The entire process, along with data collection for offline analysis, must be done in real-time at a speed high enough to minimise the calculations required to ensure equilibrium is satisfied for the overall test/model structure.

The hybrid testing procedure follows a step wise calculation process. The testing procedure is done in real time. Hence, there is no opportunity to reiterate steps in the computation, and if done rapidly enough, there should be no need or loss of accuracy relative to the dynamics of the system (i.e. much faster than system dynamics for each time step). The details of the steps follow, Figure 3 is a flow chart of the process and Figure 4 shows the device in the dynamic test rig with an illustration of the process.

Simplified Hybrid Testing Algorithm:

1. (First time step) External inputs to the main structure, such as forces due to a ground motion, are determined for the current time step. These external inputs are required to be known for the duration of the test.

2. (All other time steps) All inputs to the system are determined. These include external inputs and returned responses from the sub-structure being examined.

3. Response of the (model) structure to these external inputs is calculated and the conditions at the point of attachment/interface of the sub-structure and device being examined are determined. Conversion factors due to scaling or changes in the type of motion, such as rotational to linear motion, are applied at this point.

4. Commands, resulting from the previous stage, are sent to the test rig.

5. The test rig implements these commands (in all cases to date these have been linear displacement commands but the type of command can be of any form and is dependent on the experiment and therefore the type of test rig being used).

6. The physical sub-structure or device being tested/examined is subjected to the command and the response is measured (once again the response is dependent on the form of the experiment).

7. The response from the sub-structure is returned to the computation system where the conversion factors, if any, are again applied.

8. These steps are repeated in order for the duration of the test.

More specifically, running this system at a servo rate at least ten times higher than the system frequencies of interest minimises or eliminates the need to determine changes in equilibrium status between time steps because the errors are minimised. For the case presented, the dSpace™ system used is capable of running at least 10 input and 10 output channels at 1-10 kHz, which is far faster than any structural system requirement. Hence, no inner iterations are required to determine the necessary forces and displacements during each step. In addition, in testing structural control devices that are, unlike structural elements, highly repeatable in behaviour, there is less error or non-linearity to account for, further reducing any need to check equilibrium balances.

This system uses sin(θ) in the specific equations of motion [14] for this simple system and has the added non-linearity of impact loading, which must be accurately determined in the resulting integration scheme to avoid significant error where the structure is perceived to have moved through the fixed floor. Energy of 5% of total kinetic is assumed dissipated on each impact creating a stable system. The rocking walls considered here are realistic in size of 1-5m in height and thus the 1kHz servo-rate used is more than fast enough. The second model example considered in this paper is merely a single degree of freedom (SDOF) linear structure with 0% critical damping to demonstrate the impact of the devices in adding dissipation. While it is not in the scope of this paper to show the detailed equations, they can be found in [14].

3. BENEFITS OF HYBRID TESTING METHOD

The benefits of using the hybrid testing procedure include: real time analysis, ease of experimental setup, and the ability to quickly change system parameters during experimentation. In addition, a wide variety of possible applications can be analysed and tested perhaps far more readily as a sub-system, or as a series of disconnected subsystems. Finally, using dSpace™ and Matlab®, the computational system is contained within an easily transportable unit utilising well accepted programs and systems.

Real Time

Central to the whole process is the dSpace™ real-time control system. Due to the computational power of the dSpace™ system, fairly complex structural models can be used with no delays for data processing. Hence the experiments can be run in real time. This real time analysis can be preferable to pseudo-dynamic testing as inertial effects do not have to be additionally incorporated into the virtual analysis. In addition, the dSpace™ system does not allow continuation in the calculation process if the preceding time step analysis has not been completed. This condition ensures the simulation follows in the correct order with inputs to the system corresponding to the correct point in time of the analysis.

Easy Setup

Once again the easy set up is due to the real-time control system used. The virtual model is set up in simulink's block diagram framework, which allows easy access to sections of the model, thus allowing rapid implementation of any changes required during testing. The dSpace™ system is used for data gathering and storage. Hence there is no need for a separate system for this purpose. In addition, connection to a variety of different sensors and measuring devices presents no problems as any conversions and calibration can be incorporated into the experiment layout and controlled from the command desk.

Easily Transportable

The computation, virtual-real interface and the data recording and storage systems are all contained within the dSpace™ unit. The software is well accepted as Matlab® and Simulink® are well accepted in the field and thus readily modified by a moderately experienced user. Thus, the whole system and approach is easily transportable to different test locations or environments, in this case in a wheeled unit.

Adaptability to Different Applications

Due to the flexibility of the procedure a variety of structural systems can be implemented. The implementation of any structural system is dependent only on the ability to model the main/virtual structure sufficiently to capture the necessary structural dynamics and on an external testing machine or actuators that can supply the necessary commands, dictated by the response analysis of the virtual structure, to the sub-structure. The developed test method can readily adapt to difference applications. The applications tested to date include a single-degree-of-freedom system with a device attached between the structure mass and the ground and a rocking wall panel where the device acts as a ‘smart’ tendon to control the rocking dynamics of the wall.

Control Prototyping

For the design and testing of complex control systems and their algorithms under real-time constraints, a real-time controller simulation with control hardware other than the final series production hardware (e.g., special computer control hardware) may be performed. The process, the actuators, and sensors can then be real. The control algorithm can be developed in the hybrid testing environment without the final control system. Such a process of control prototyping shortens the development cycle.

4. LIMITATIONS AND SOLUTIONS

The problems associated with development of the hybrid testing method include:

1) signal processing lag;
2) optimising sensing resolution; and
3) bandwidth and efficient model computation.

The last of these is largely a trade-off between model complexity, model accuracy and fast computation.

Signal Processing Lag

Signal processing lag is the time difference between completion of the computation for a particular time step and the time when the signals from the external ‘physical’ system are received. These two signals are both required before the subsequent time step calculation can commence. If data from these two sources is not synchronized the overall system may become unstable due to the system changing dynamic state during the computational period.

An example of this instability occurs with a simple single-degree-of-freedom structure with a single displacement based structure control device attached between the ground and the structure mass. If the virtual structure has been calculated to have changed direction and the external signal from the physical device lags behind, it will appear to the calculation system that the device, instead of resisting the structure motion, is pushing the structure, hence adding energy to the overall structural system. This spurious condition can be removed by using the returned commands instead of a combination of computed and measured signals, thus ensuring the main structure and sub-structure conditions are consistent at each time step calculation.

Optimising Sensor Resolution and Sensor Bandwidth

The clarity of the returned (measured) signals can have a significant effect on the quality of the analysis. If these signals have excess noise it is very difficult to determine the true signal, and thus to run the system properly and accurately. However, if the signals are filtered to provide a clearer signal, the lag between the calculated response and the corresponding returned values increases and the possibility of instability, as discussed previously, increases.

Figure 5 shows a portion of a typical displacement signal with a large amount of noise in the signal. Figure 6 is the FFT of the displacement signal showing the typical harmonic noise peaks due to mains power. This less than desirable effect was removed by using linear potentiometers for displacement measurement instead of the internal displacement sensor in the dynamic test rig. These potentiometers have the additional advantage of allowing manual calibration and zeroing, something that was not possible with the internal displacement measurement. Thus, they reduce noise and add bandwidth in terms of the specific hardware used here, allowing a faster, cleaner signal with less lag.

Efficient Model Computation

Model efficacy is a trade off between rapid calculation and accurate representation of the structural dynamics. The computational power of the dSpace™ system is significant, although the models used here have not been complex. If large complex models were required, the structural calculations and data management could be separated onto two dSpace™ chips to optimise the method. Overall, this issue best managed by using the most efficient model with the necessary dynamic accuracy.

A second point in this regard is the use of efficient computational schemes. Since the model is simulating every time step, the first major point will be to efficiently compute that model's behaviour to provide inputs to the hybrid system. The second major requirement is to ensure that it is a stable method that allows a time step that matches the system, minimising extra intra-time step computations.

Fortunately, for structural systems a very efficient approach exists. This approach is unconditionally stable at any time step size and is, importantly, incremental. Thus, the system only need compute the current time step increments and add them to the prior summed values. Specifically, this paper used an unconditionally stable, incremental Newmark-Beta constant average acceleration method. For simplicity it is shown here for a single degree of freedom system of mass, *m*, damping, *c*, stiffness, *k*, and input force, *f*, where subscript *j* is the current time step number [17, 18]:

$$\left(\frac{4}{\Delta t^2}m + \frac{2}{\Delta t}c + k\right)\Delta v_{j,j+1} = f_{j+1} + m\left(\frac{4}{\Delta t}\dot{v}_j + \ddot{v}_j\right) + c(\dot{v}_j) - k(v_j) \tag{1}$$

$$\Delta\dot{v}_{j,j+1} = \frac{2}{\Delta t}\Delta v_{j,j+1} - 2\dot{v}_j \tag{2}$$

$$\Delta\ddot{v}_{j,j+1} = \frac{4}{\Delta t^2}\Delta v_{j,j+1} - \frac{4}{\Delta t}\dot{v}_j - 2\ddot{v}_j \tag{3}$$

Where Equations (1)-(3) are solved in that order every time step. After that time step the values of displacement, *v*, and its first and second derivatives (velocity and acceleration) are updated by their increments, such that: $v_{j+1} = v_j + \Delta v_{j,j+1}$; $\dot{v}_{j+1} = \dot{v}_j + \Delta \dot{v}_{j,j+1}$; and finally $\ddot{v}_{j+1} = \ddot{v}_j + \Delta \ddot{v}_{j,j+1}$.

Note that for non-linear systems this system is readily extendable, as well as for vectorising it for multiple degrees of freedom [17]. In the non-linear case, this method can be extended to include an incremental or total equilibrium check for which any small differences are adjusted for in the next step, as an added force [17, 18]. In the multiple degrees of freedom case the matrices that results for Equations (1)-(3) can be readily pre-calculated as they are constant and thus, they and their inverses, as required, can be pre-stored in memory to further minimise computation. Additional computation minimisation strategies include pre-storing the resulting matrix equation multiplication results for Equations (1)-(3), in this multiple degree of freedom case, as well as storing and re-using calculations or patterns of calculation that re-appear in these solutions. Overall, this approach can minimise computation for even several hundred degrees of freedom to a level that will fit within the constraints of many common, current target chipsets.

5. EXPERIMENTAL RESULTS and DISCUSSION

Extensive experiments have been conducted to validate the testing method. Figure 7 shows how the single DOF structure responds to a sinusoidal 0.4g, 0.5Hz ground motion. The structure has a mass of 1000kg and structural damping of 5%. The force response is small due to the piston displacement being small (<10mm) relative to the maximum allowable displacement (34.5mm). The structure displacement, which is identical to the device piston displacement, is not altered much from the uncontrolled case. However, this test was done to validate the hybrid testing procedure rather than to prove the efficacy of the resetable devices at improving structural performance, which is examined in other work. The results below show the full feed-back response. Also note that the device response under 2-4 control looks a lot like the ‘optimum shape’ due to delay from data filtering and non-instantaneous energy release time.

Figure 8 show theoretical response of a rocking wall without and with an actuator to a ground motion. Changes in the rotations, both in size and time can be seen, with the result depending on the height of the wall and the relative timing between the large pulses of the ground motion.

Figure 9 shows experimental data of three different earthquake records. Each earthquake record shows four diagrams, namely, the ground motion, the rotation of wall for the uncontrolled (dashed line) and controlled (solid line), the response force as a function of time, and the response time as a function of the wall rotation.

The actuator was not getting into the high force range because the displacements were not large enough. Control type is 1-3 as with a rocking wall to resist the outward rocking and then allow ‘free’ motion on the return rocking section. Some type of displacement amplifying mechanism would be required to increase piston displacement into the large force zone of the device. However, reductions in rotation of the wall are evident in all three earthquake records.

The results prove that the hybrid testing procedure works. It is possible to feed back the device response in *real time* to the computation model which has sufficient capacity to do the necessary calculations in each time step. In addition, the system is robust in terms of relative timing of signals and filtering to avoid instability.

In Figure 9, the record (C) shows an interesting looking hysteresis loop for the device. The motion was more in one direction for one rocking cycle, resulting in apparent asymmetric response from the device. However, such an approach in using this simplified hybrid testing allows these potential issues to be discovered at an early stage and before an expensive, fixed and/or large scale experiment is designed.

In Figure 9, the results differ across the different earthquakes applied to the structure in hybrid testing. This result shows how making a single or a few tests of a large experiment might lead to misleading results, especially for non-linear systems like rocking structures. In particular, during a full scale test one might see the better results of A and B or the no-difference result of plot C in Figure 9, leading to a false conclusion in any event. In this case, with hybrid testing the range of possible outcomes can be seen as many more such ground motion events can be tested on the hybrid system, and thus the full scale experiment can be better designed to highlight the full range and potential of the test device or structural system. Importantly for the simplified system presented in this paper, this task can be done at a very low computational, time and financial cost to the research engineer, enabling an overall better research or design outcome

6. APPLICATION EXAMPLES and DISCUSSION

This section presents two hybrid test example applications using dSpace™. The primary focus is based on recent research into seismic mitigation devices and systems. In particular, the development of semi-active systems and structures enhances seismic energy management.

A section of a rocking structure (one rocking wall panel) is used as the first example to demonstrate the results obtained using the hybrid testing procedure [11]. In this application the external input is the ground motion. The computation model calculates the response of the wall in terms of the angle theta (rotation about the bottom corners of the wall), which is converted into a linear displacement command sent to the dynamic test rig (in this case the corresponding displacement of the actuator if it were in place in the wall). The result from the physical device being tested is then returned and used as an input to the subsequent calculation step. Figure 10 shows these signals, and Figure 11 illustrates the slight difference between the command sent to the dynamic test rig and the actual dynamic test rig actuation.

Figure 12 demonstrates the types of discovery that results from using the hybrid testing procedure. In this case, for the particular ground motion, it is observed that the addition of the device to the structure system results in a better response for the small rotations but not for the initial large rotations. If only one particular ground motion was examined with full scale testing, the resulting conclusions made could be biased either for or against the particular sub-structure or device being examined. Thus, hybrid testing offers the possibility to examine the structure response to a variety of situations and choose the most appropriate tests to take through to full scale testing.

The second example involves a linear single-degree-of-freedom structure used to generate experimental response spectra using a physical, non-linear test device [10, 14,16]. The results are shown for the force-displacement hysteresis loop and seismic response in Figure 13. This second example has similar results and exactness to the first rocking wall example. In this case, the non-linearity of the device is more evident in contrast to the linear one degree of freedom structural response. Note that the hysteresis loop shown as a combination of a linear, undamped structure and a non-linear device in Figure 13 is the desired outcome. It does not affect equilibrium of the model or device in this hybrid test approach because the model takes only resulting forces (and motions) as inputs to the model, and these already encapsulate the hysteresis. Again, the hysteresis is the desired outcome of using such a non-linear device [10,11,14,16].

Overall, both examples demonstrate the accuracy and potential of this "real-time pseudo-dynamic" or hybrid test approach. The main outcome of the work presented is the ability to simply and readily implement this type of test system using the dSpace™ real-time prototyping system. A second outcome is the delineation of the fundamental experimental design tradeoffs that arise in this type of experimental procedure. Finally, the examples presented in this section also illustrate the particularly effective use of this test approach for analysing novel structural devices.

The accuracy or perfection of the model used to represent the rest of the structure is not as important as might be perceived in fully structural testing applications, especially when testing devices. In particular, as long as the model provides a "strong" representation of behaviour it will meet the needs for this type of simplified hybrid testing. More specifically, a goal of this approach is to test systems before building large experiments. This approach means that a good representative model will show the range of possible behaviours and inputs a device might receive. It thus allows the designer to modify the device or design it explicitly for the application, as was done for the large experiments in [14] using similar semi-active devices.

Finally, it remains to put this system into context. The most recent advances for structural engineering, control and such devices in particular, is in terms of the NEES project [15]. This project offers "real-time hybrid testing" but does so over the internet. However, the realistic rates of control are on the order of 0.1-3.0 seconds. Thus, it cannot enable dynamic real-time testing resulting in a pseudo-dynamic test only, per normal approaches in the field. Note that pseudo-dynamic testing is well accepted [4-6] and works well for large structural test articles where the actuators and forces required for dynamic testing, as well as the rigid solid reaction walls required, are not readily available. However, for devices these slow tests miss the point entirely as they are dynamic devices with their own dynamic, higher frequency (higher than pseudo-dynamic testing excites) responses. It is these behaviours that the method presented here wishes to test and analyse. Thus, this approach is quite unique in the field in both its speed, as well as its focus on structural control or similar devices.

Finally, this paper has presented some simplified examples and shown the basic elements of the system or approach. It has also emphasised simple or efficient models. This criterion is increasingly not a major issue in such applications. A current embedded processor in dSPACE™ or similar system is quite powerful and can manage with substructuring or other well known analysis techniques a very large model in an effective real-time basis of 0.1-1.0 kHz or more. For example, a 1GHz processor can perform 1M computations in one time step if operating the system at 1kHz as was done here. Thus, a very large model can be managed for solutions over 1 time step in that number of operations. Therefore, the overall limit of this approach is not necessarily the small models studied here.

The system is robust given the use on a non-linear system in the rocking wall example. This rocking wall example is non-linear and not necessarily stable as it can overturn given the right combination of forces. That said, over 60 earthquake inputs used in the entire hybrid test series [11,14], the system managed all outcomes without loss of equilibrium in the model or results that did not match simulation alone. In particular, using the measured forces and device displacements from the experiments as inputs to a simulation of the rocking wall model, yields effectively the same rocking wall response angle over time showing a strong measure of overall system design robustness.

7. CONCLUSIONS

The hybrid test method developed here illustrates the efficacy of a cost-effective and easy-to-implement system that is applicable to a wide variety of structural systems. A dSpace™ system that utilises well-accepted Matlab® and Simulink® programs is used to rapidly develop a real-time system with minimal time or overhead. The process runs in real time and has been demonstrated at rates up to 10 kHz. Thus, the computation does not need to incorporate additional complexity to account for inertial effects or inner equilibrium iterations as the system dynamic change in a time step – a significant advantage over existing approaches.

This approach enables a large number of tests to be accomplished in a short period using smaller, more easily made substructures, or in this case, repeatable structural devices. Hence, a stronger test series can be run prior to full-scale testing. As a result, the final outcome of the full-scale test can be far less variable or unknown in the event.

Overall, the system is simple and enables any lab with this type of system to develop this capability quite rapidly. The use of hybrid testing is growing in structural engineering design and is thus becoming more of an important capability for many labs. Hence, the method presented, utilizing off-the-shelf products and proven real-time systems, creates a well-accepted and transferable test method and environment.

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Captions of Figures

Figure 1: Example of a physical structur

Figure 2: Computer model of the civil structure
Figure 3: Flow chart of the hybrid algorithm showing the physical and virtual (computer model) boundaries. At each time step the information exchanges shown are made. The commands are displacements to the structural control device or test structure, as well as any device command if the device is active or semi-active in nature. The returned signals are forces and resulting displacements or velocities. These signals are further defined in Figure 4 and the algorithm shown.

Figure 4: Dynamic test rig for the semi-active structural control device and the computer modeled structure that is seismically excited. The device is presumed to be within the structure modeled and the two interact to test the robustness of the device to simulated structural scenarios before full scale testing. The schematic also shows the signals that cross the physical-virtual interface or boundary. All calculations are done on the computer in real-time.

Figure 5: Typical LVDT signal with noise due to electric mains interfence. The noise is on the order of 0.03mm rms which is enough to affect the resolution in testing if displacements are small.

Figure 6: FFT of the displacement signal of Figure 5 showing frequency peaks associated with noise caused by electric mains power

Figure 7: Response of single degree-of-freedom to a simple sinusoidal ground motion

Figure 8: Theoretical response of rocking walls of different heights (H) an fixed width (1m) to a g

Figure 9: Experimental hybrid test results for three different earthquake records.

Figure 10: Typical results from a hybrid test

Figure 11: Close up comparison between the command signal displacement calculated for the device by the computer model and sent to the device across the physical virtual boundary and the returned measured signal

Figure 12: Virtual structure response with and without the addition of the physical device being examined.

Figure 13: Force-displacement response of a single-degree-of-freedom structure and the attached actuator (the sub-structure being examined being a semi-active actuator).

Figure 1: Example of a physical structural experiment, a portion of a full structure to be tested experimentally. The full structure is shown in Figure 2. The main focus of such a study is typically the behavior of the structural connection design that is circled in this figure, and its interaction as part of the whole remaining (simulated in hybrid or pseudo-dynamic testing) structure.

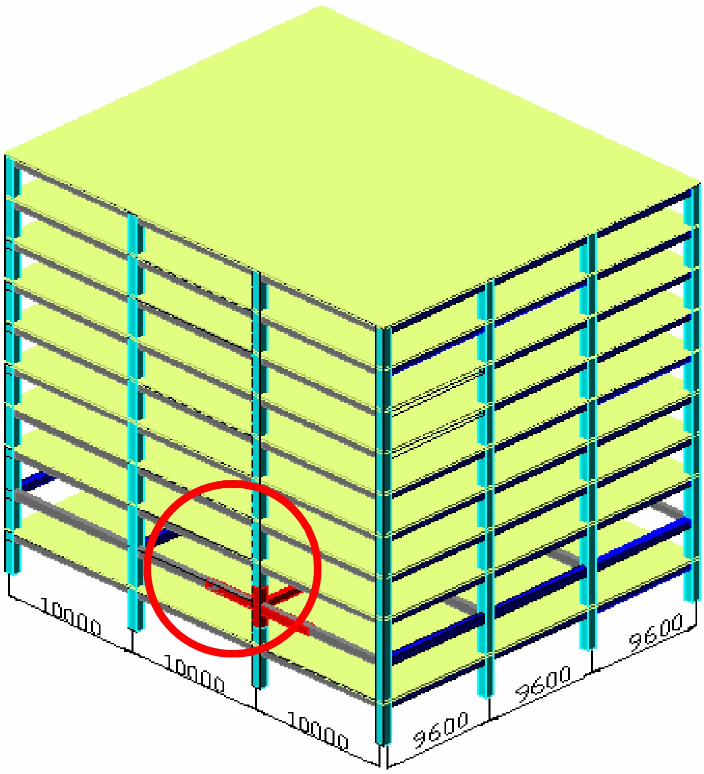


Figure 2: Computer model of the civil structure to be tested showing the removed portion that is physically tested. Thus, the physical portion in Figure 1 and the remaining structure are examined together where the portion in this figure is simulated via computer model and the circled portion of Figure 1 is physically tested as if it were part of that overall, seismically excited structure.

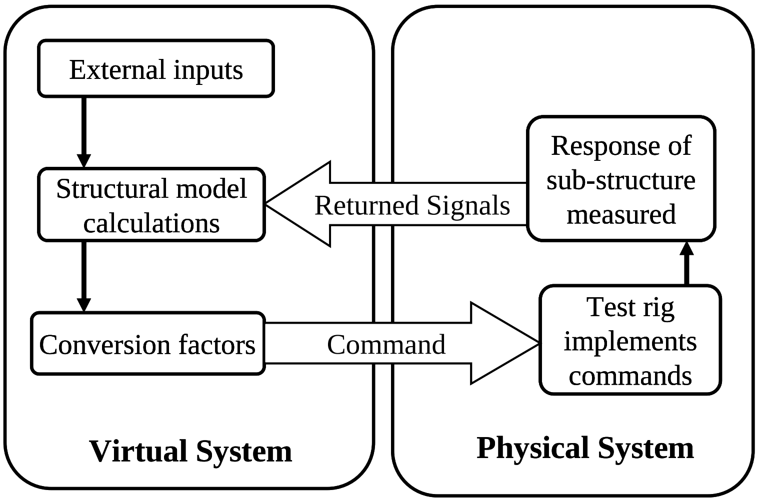


Figure 3: Flow chart of the hybrid algorithm showing the physical and virtual (computer model) boundaries. At each time step the information exchanges shown are made. The commands are displacements to the structural control device or test structure, as well as any device command if the device is active or semi-active in nature. The returned signals are forces and resulting displacements or velocities. These signals are further defined in Figure 4 and the algorithm shown.

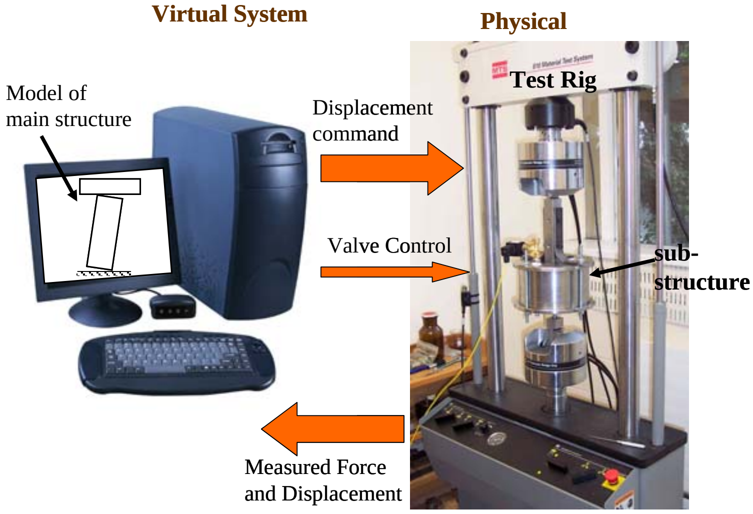


Figure 4: Dynamic test rig for the semi-active structural control device and the computer modeled structure that is seismically excited. The device is presumed to be within the structure modeled and the two interact to test the robustness of the device to simulated structural scenarios before full scale testing. The schematic also shows the signals that cross the physical-virtual interface or boundary. All calculations are done on the computer in real-time.

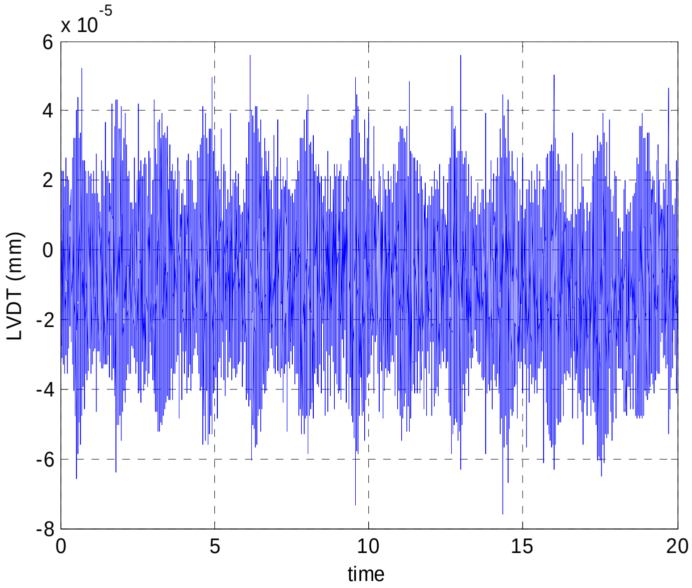


Figure 5: Typical LVDT signal with noise due to electric mains interfence. The noise is on the order of 0.03mm rms which is enough to affect the resolution in testing if displacements are small. Note that this is the zero (0) input case where it attempts to measure a displacement of 0mm. Larger motions can have larger error as the signal is affected proportionally.

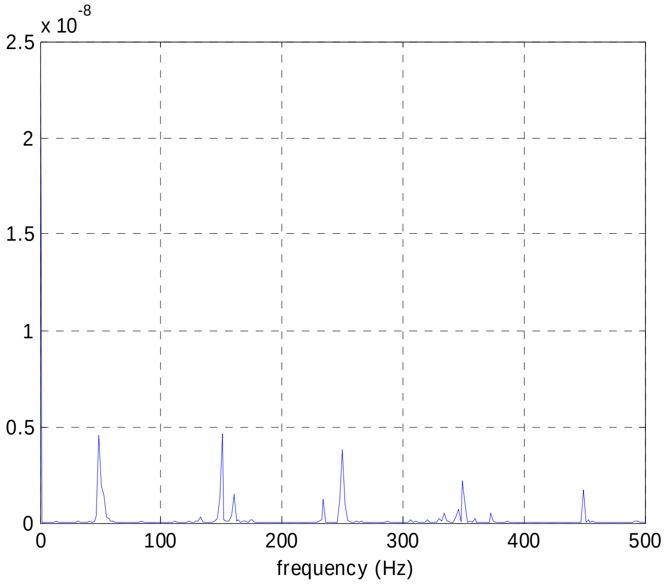


Figure 6: FFT of the displacement signal of Figure 5 showing frequency peaks associated with noise caused by electric mains power at 50, 150, 250, 350 and 450 Hz, or odd multiples of 50Hz which is the typical location for such noise in New Zealand.

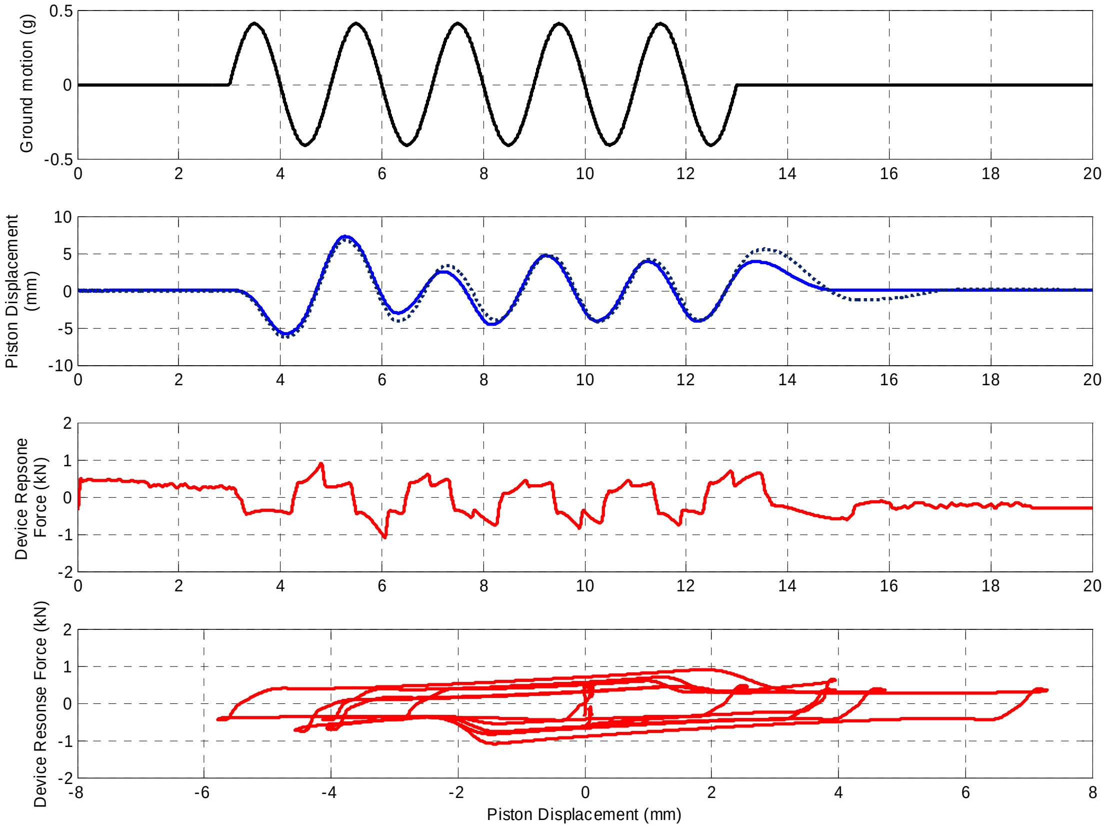
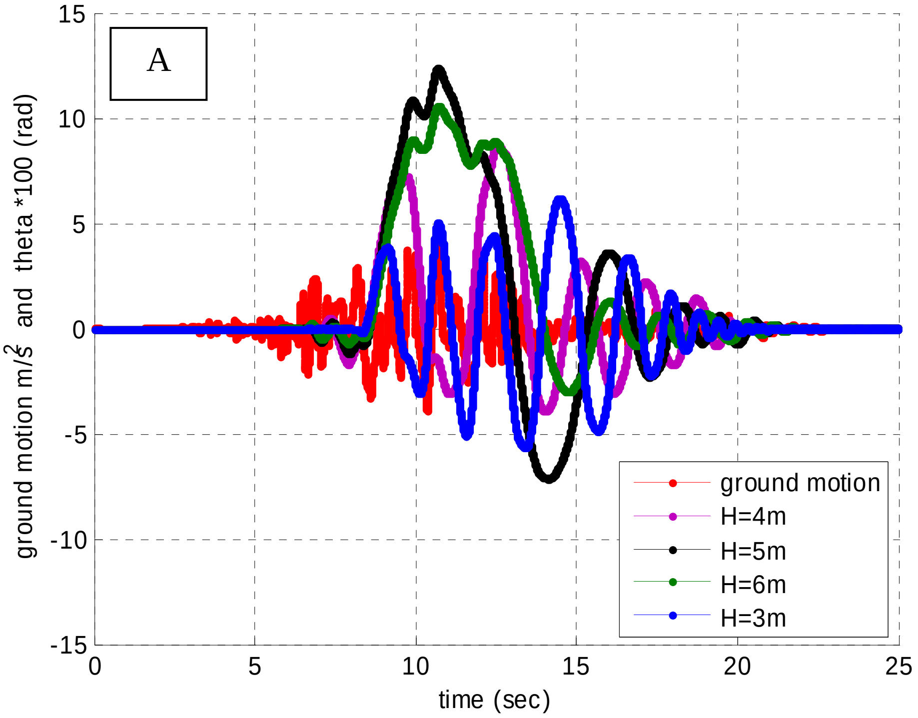


Figure 7: Response of single degree-of-freedom to a simple sinusoidal ground motion in the top plot. Results are both with and without control The dashed line in the second piston displacement plot is the uncontrolled case for comparison. The third plot shows device force over time and the fourth device force as a function of physical piston displacement in the hybrid test.



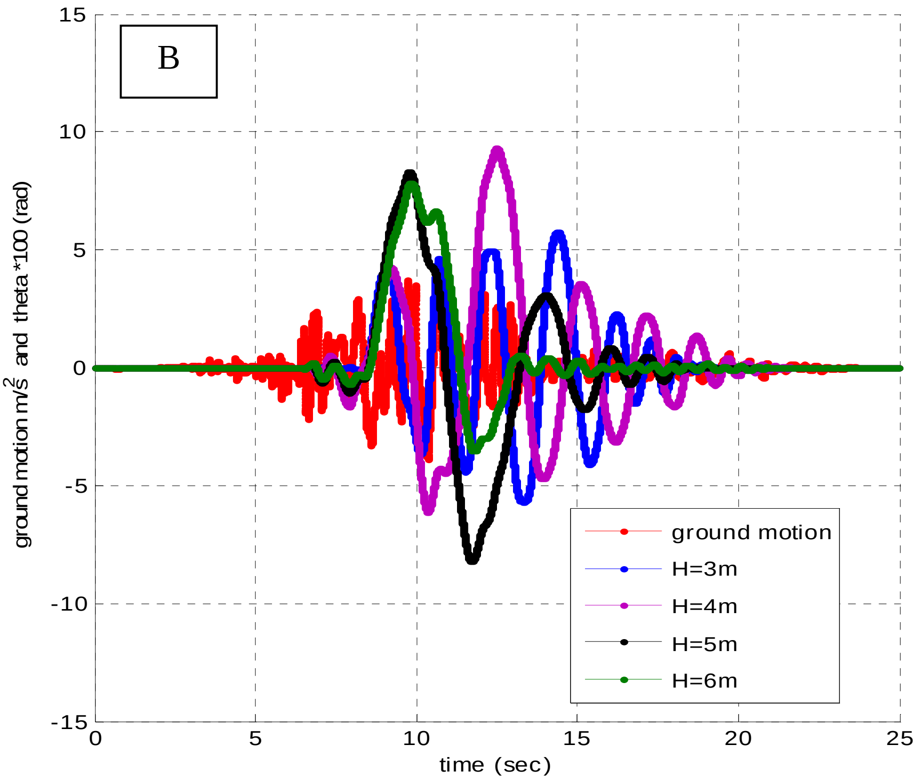
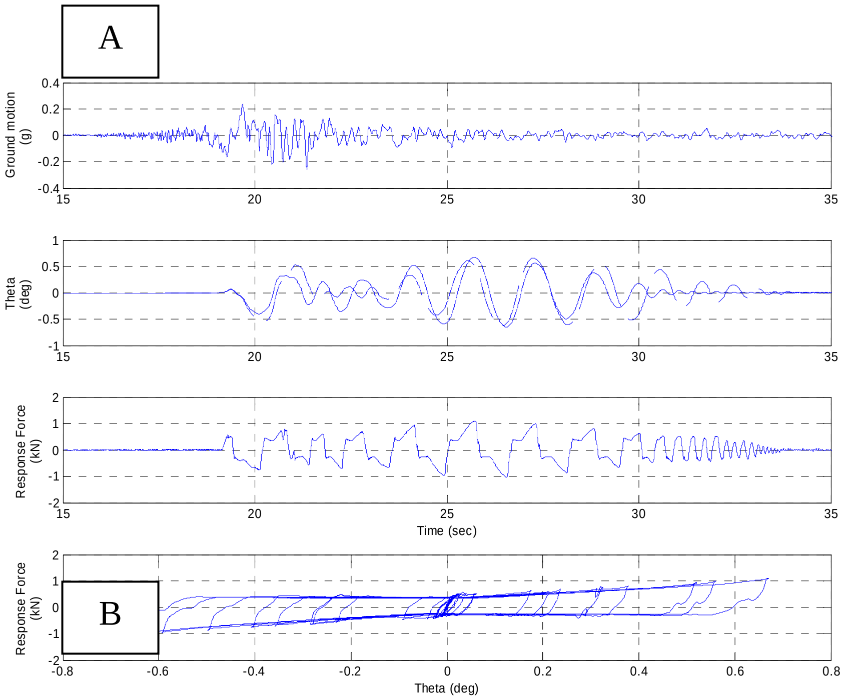
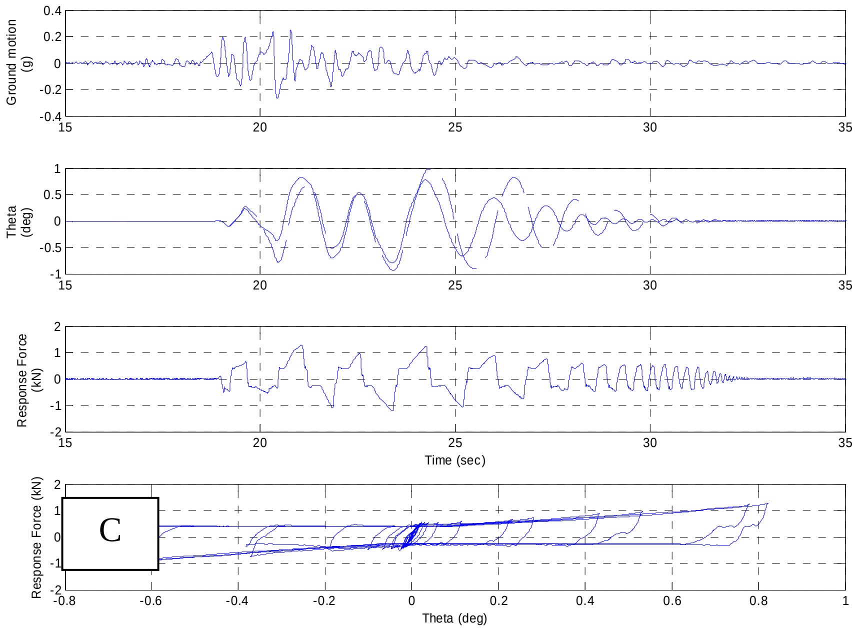


Figure 8: Theoretical response of rocking walls of different heights (H) an fixed width (1m) to a given ground motion, which is also shown. A) uncontrolled and without an actuator and B) controlled with an actuator for which results are generally smaller over the time period shown. Note that the response shown is angle theta in radians * 100 to provide a relative scale for comparison only. The ground motion input is in m/sec^2.


A
Ground motion (g)
Theta (deg)
Response Force (kN)
Time (sec)
B
Response Force (kN)
Theta (deg)


Ground motion (g)
Theta (deg)
Response Force (kN)
Time (sec)
C
Response Force (kN)
Theta (deg)

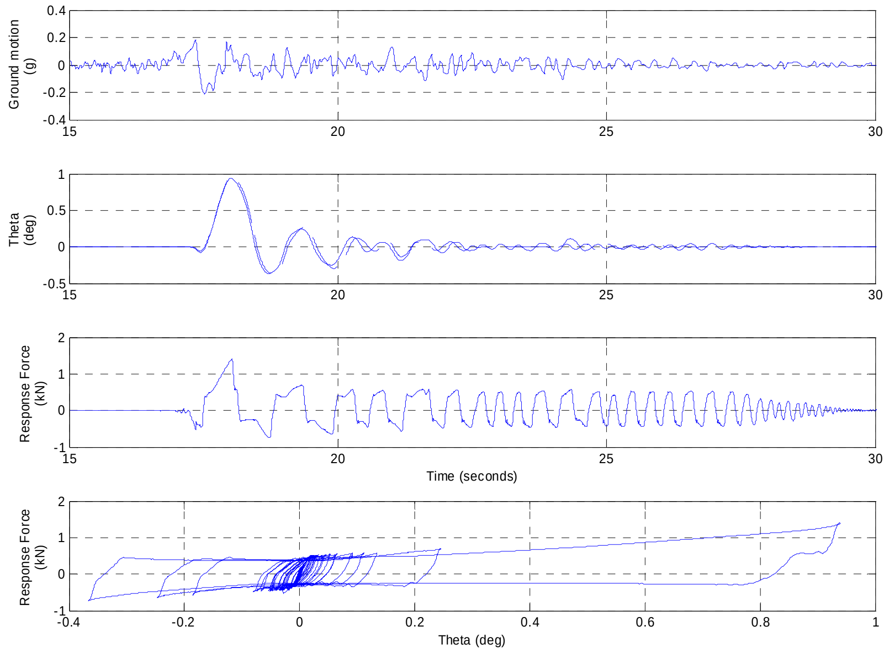


Figure 9: Experimental hybrid test results for three different earthquake records. The first plot in each case is the ground motion, which are all quite different. The second plot is the displacement response of the rocking wall, theta, in radians/sec for the controlled (solid line) and uncontrolled (dashed) case. The third plot is device force (kN) over time and the last plot is force vs displacement theta. Importantly, note that the controlled response for a rocking wall is not always smaller or very different from the uncontrolled response, indicating that rocking wall non-linearity over a real ground motion input can lead to very different results. This variation is one reason that hybrid testing that is low cost and simply implemented can be used to provide an idea of the range of results that might be seen before building a large, expensive test.

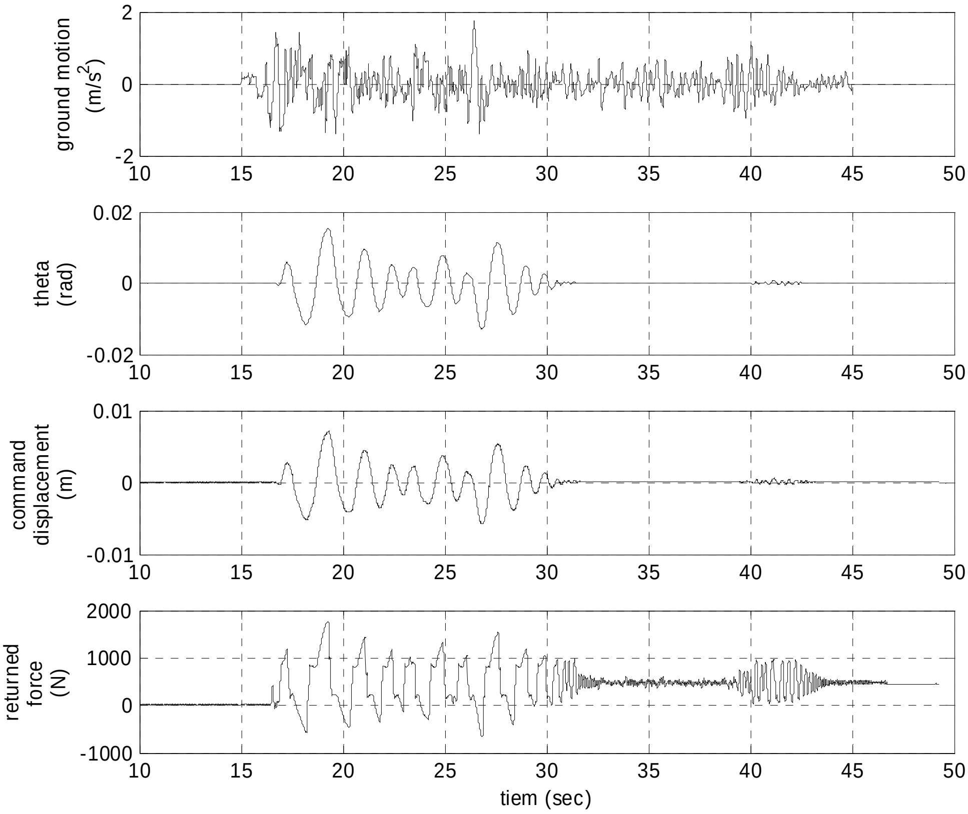


Figure 10: Typical results from a hybrid test showing the hybrid test signals. In particular, the top plot again shows the ground motion. The second plot shows the response of the rocking wall, theta. The third plot shows the commanded device displacement for the semi-active control device. The last plot shows the returned device force used in the algorithm to interact with the hybrid test computer model of the rocking wall.

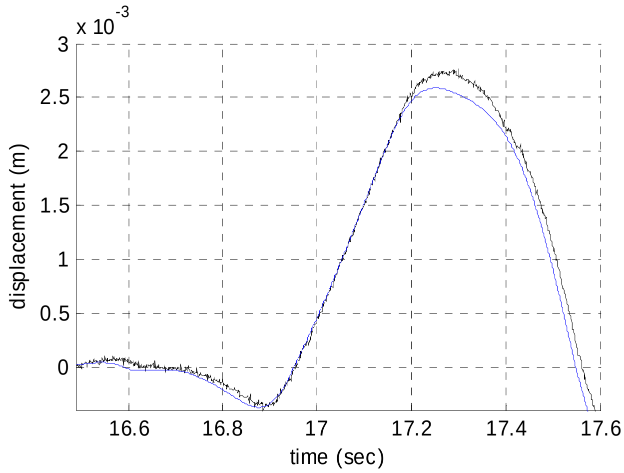


Figure 11: Close up comparison between the command signal displacement calculated for the device by the computer model and sent to the device across the physical virtual boundary and the returned measured signal from what was actually input to the device. The noisier line that is slightly higher by ~0.1-0.2mm (5-10% maximum) is the measured signal. Note that peaks show the greatest difference and the difference here is largely due to inability of the test machine to fully manage the inertia involved and lags in command signals, even at the very fast 1kHz rate used in this study.

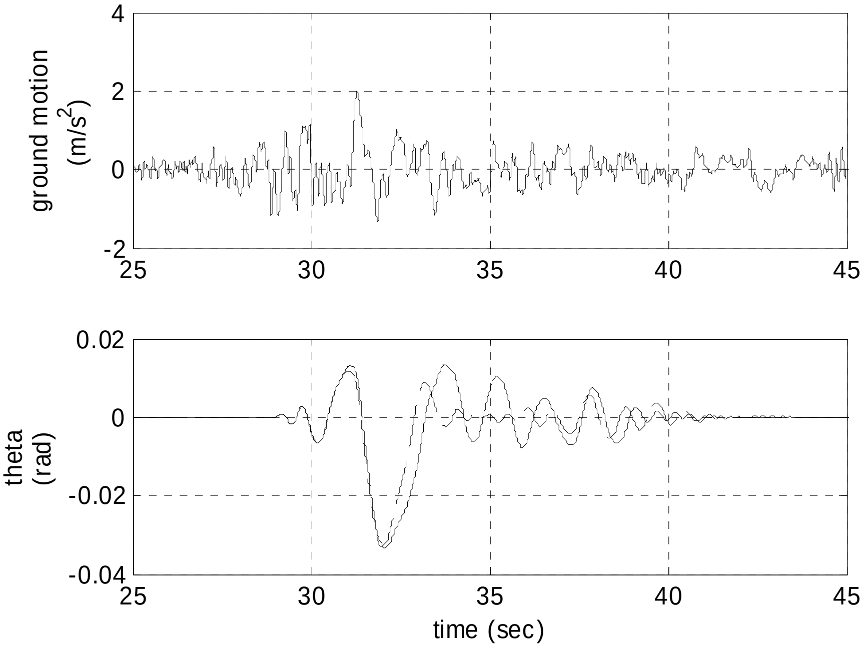


Figure 12: Virtual structure response with and without the addition of the physical device being examined. The top plot shows the ground motion and the bottom the response of the modeled wall.

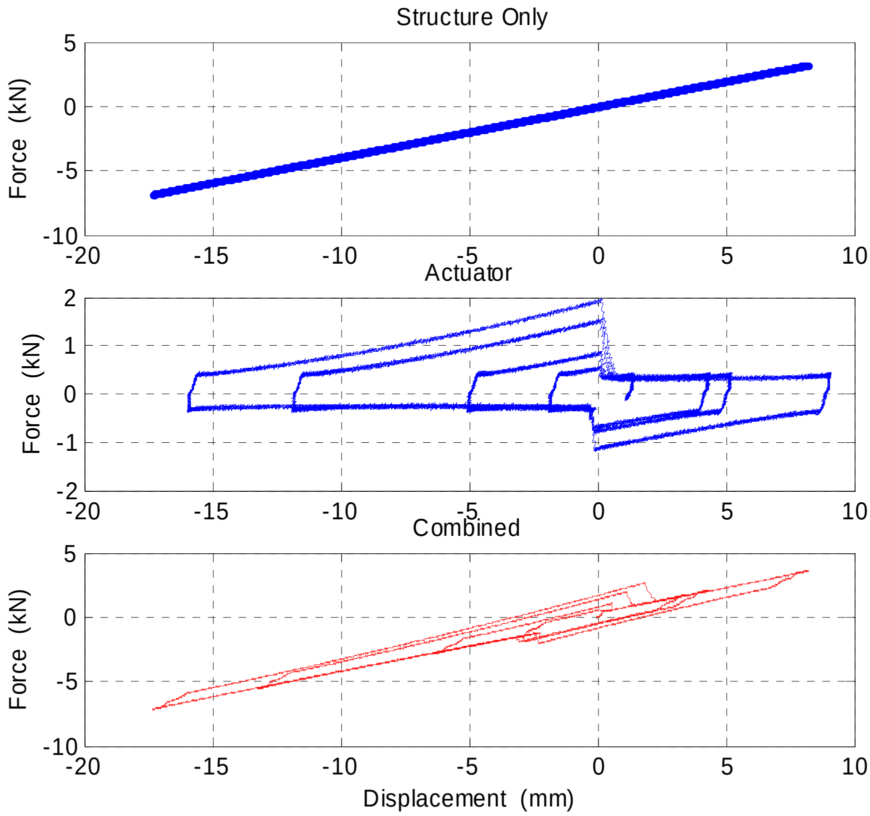


Figure 13: Force-displacement response of a single-degree-of-freedom structure and the attached actuator (the sub-structure being examined being a semi-active actuator). The combination shows how the device acts to add the expected dissipation to the overall structural hysteresis loop.